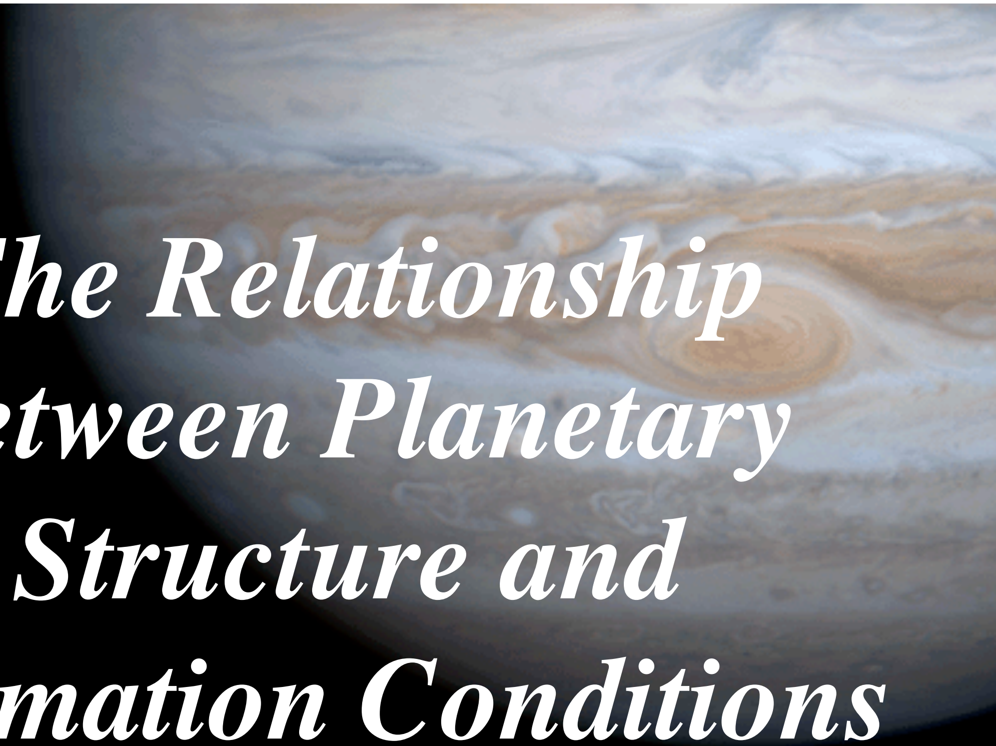


The Relationship between Planetary Structure and Formation Conditions

Dave Stevenson

Caltech

JPL/Caltech Workshop, March 19, 2008

How do we assemble planets?

It is not straightforward!

Some Guiding Principles

- Planetary structure tells us about the assembly process
- Cores of planets are particularly valuable as memories of formation.
- Composition is related to the radial location of formation?
- Extrasolar planets give us clues?

Some Significant Facts for Our Solar System

- Jupiter & Saturn are mostly gas. (So they must have formed in the presence of a nebula).
- Jupiter may have a dense core & Saturn almost certainly has a dense core. Both are enriched in heavy elements throughout. [Ar/H] = 3 x solar in Jupiter, suggesting delivery of T= 40K material.
- In situ formation of large satellites.
- Uranus and Neptune exist! And largely formed while nebula was around, because they have several Earth masses of gas. Not layercakes!
- All the terrestrial planets have liquid cores. And earth's core has superheat.

Giant Planet formation*

General but possibly vague inference

Specific but potentially very diagnostic

Observations of extrasolar planets

Observations of our solar system

*includes ice giants

Giant Planet formation*

General but possibly vague inference

Specific but potentially very diagnostic

Observations of extrasolar planets

Observations of our solar system

Complementary (you hope)

*includes ice giants

Terrestrial Planet formation

General but possibly vague inference

Specific but potentially very diagnostic

Observations of extrasolar planets?

(Not yet)

Complementary (you hope)

Observations of our solar system

Terrestrial Planet formation

Specific but possibly vague inference on process

Specific but possibly vague on timing

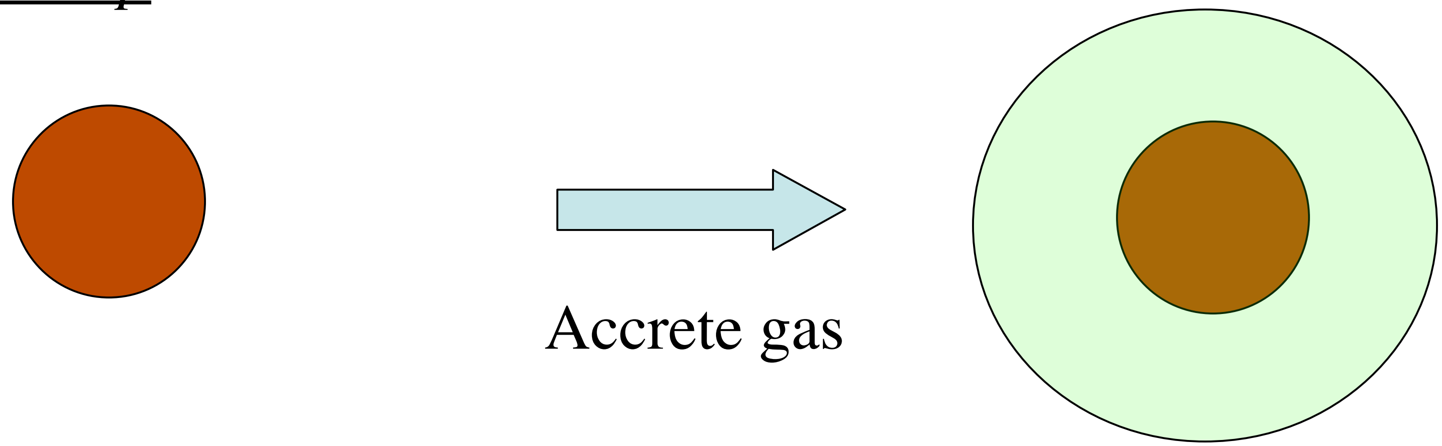
Geochemistry & cosmochemistry

Complementary (you hope)

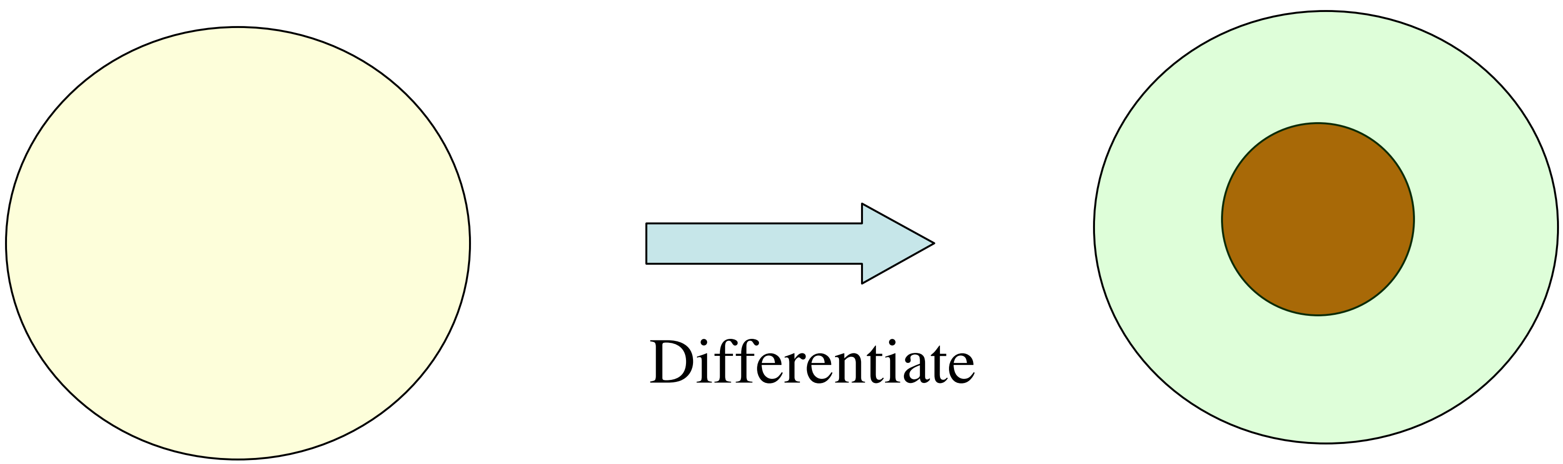
Observations of terrestrial planetary structure

Why might a Planet have a Core?

Bottom Up

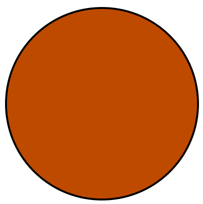


Top Down



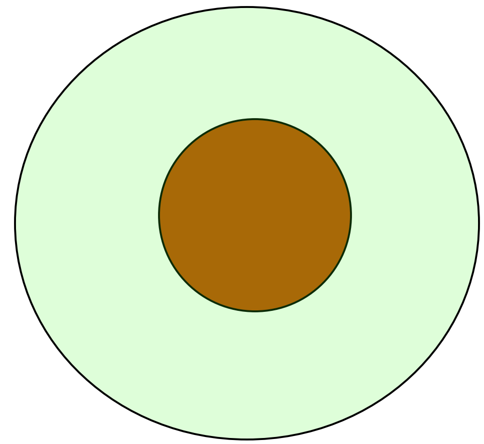
Why might a Planet have a Core?

Bottom Up

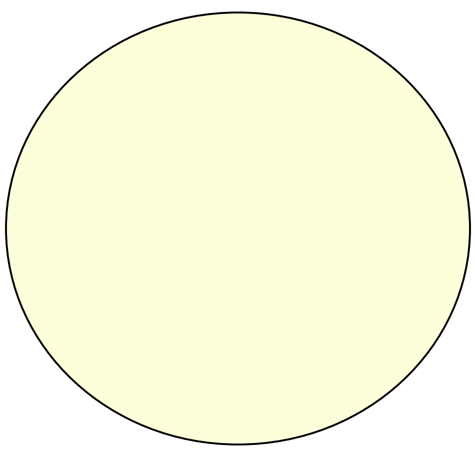


Popular Giant
Planet Picture

Accrete gas

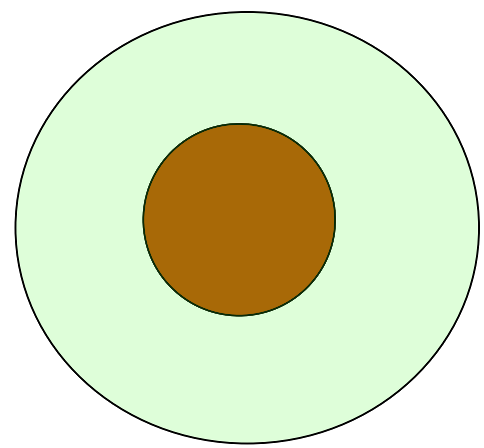


Top Down



Well established
Terrestrial
Planet Picture

Differentiate



Jupiter

- Approach to metallic conduction achieved in hydrogen at 0.85 Jupiter radii.
- Factor of three enrichment of heavy elements
- Presence of core not certain, but up to ~10 Earth masses

- **In 1974 we thought that Jupiter had a dense (rock/ice) core ~5 or so Earth masses**

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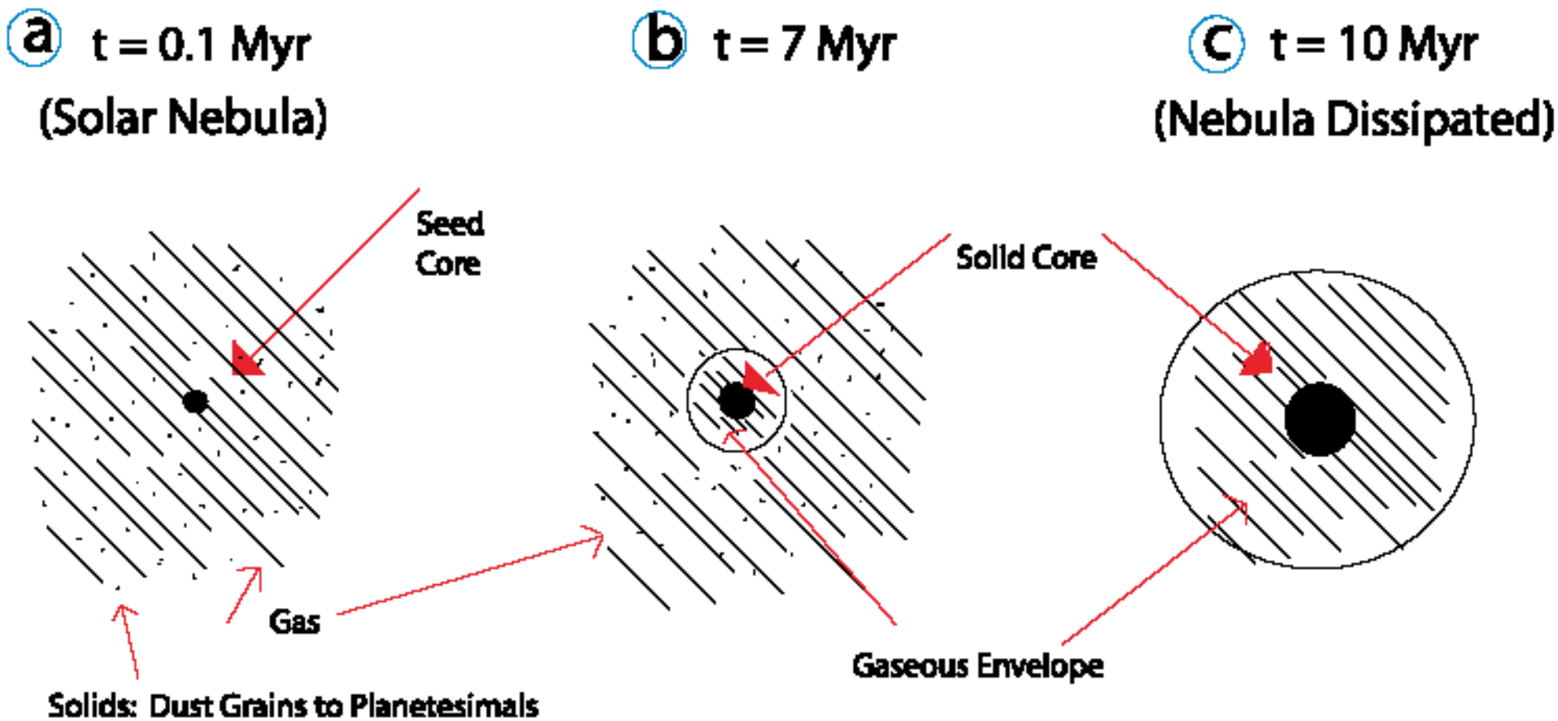
- In 1974 we thought that Jupiter had a dense (rock/ice) core ~5 or so Earth masses
- In 2006 we are not sure if this core exists!
- **Recent work (Militzer & Hubbard) suggests 15 Earth masses**
- **The main reason for this uncertainty is the behavior of pure hydrogen at 0.5-5 Mbar. We need to know this to better than 1% accuracy (1% of 315 earth masses is ~ core mass).**

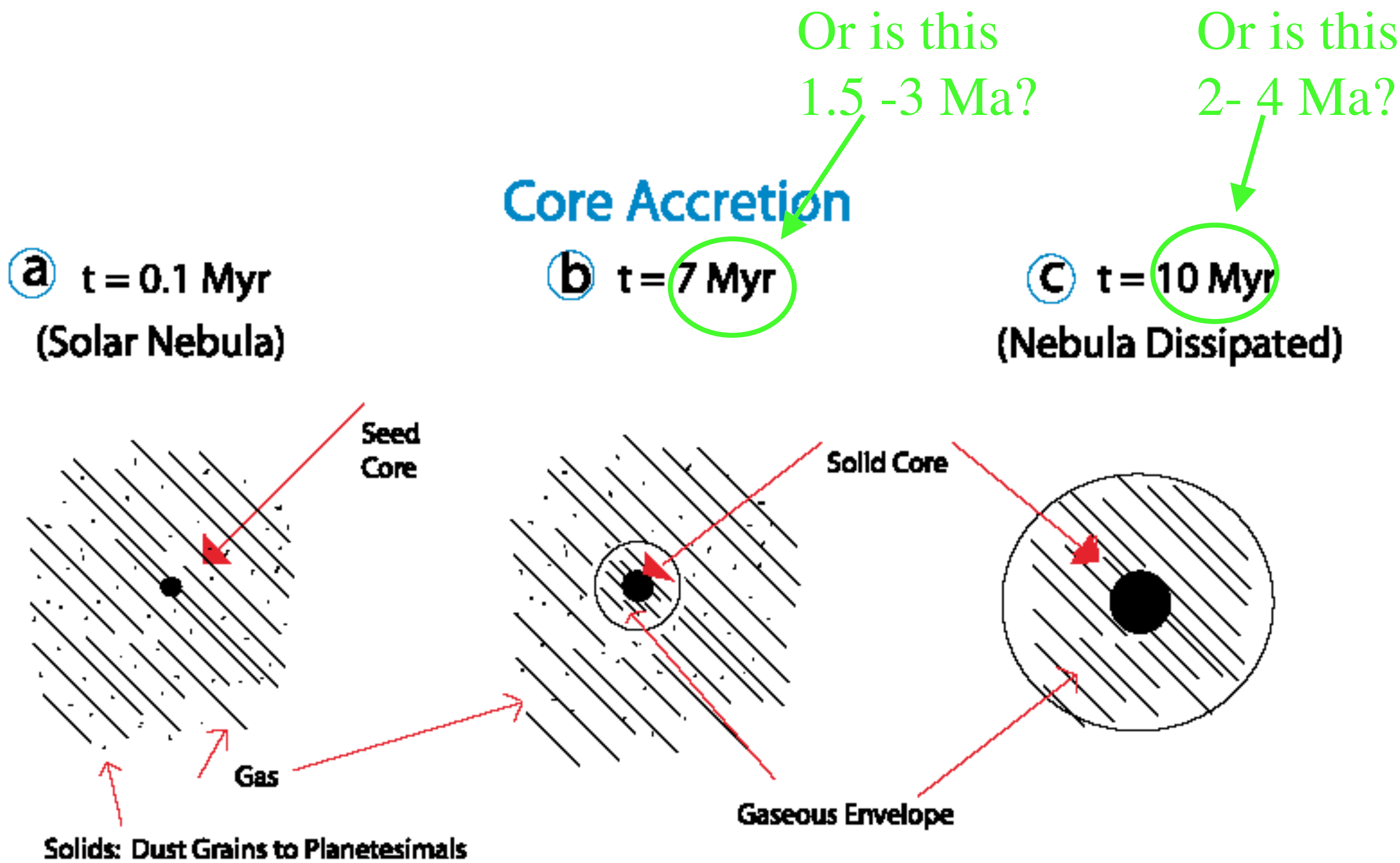
Two models for Giant Planet Formation

- Core accretion: Build a solid embryo then add gas.
- Disk instability: Direct gravitational collapse from the gas phase (analogous to Jeans instability)

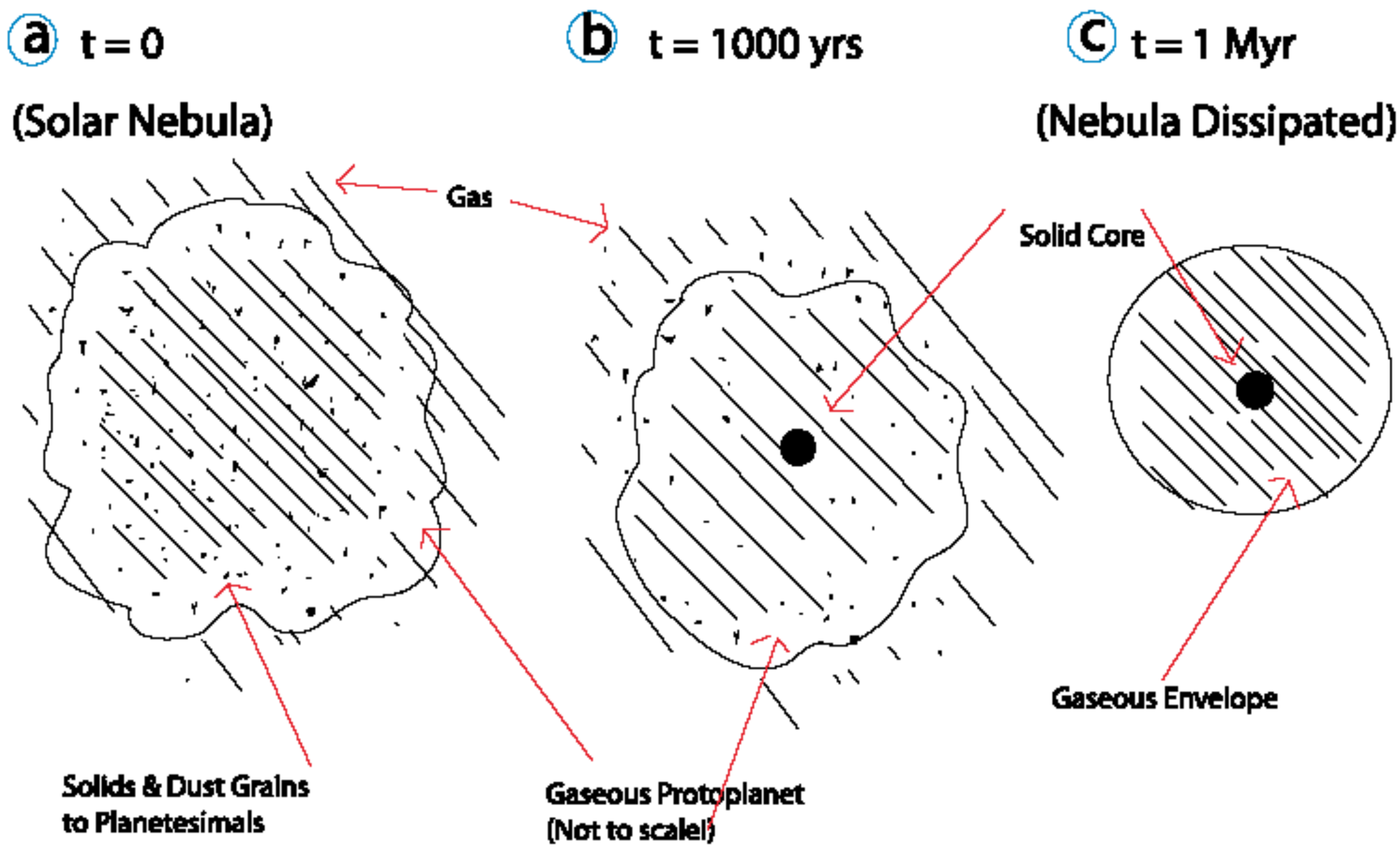
Core Accretion



Cameron (mid ‘70s)
Mizuno(1980)


Or is this
1.5 -3 Ma?
Or is this
2- 4 Ma?
Core Accretion
a t = 0.1 Myr
(Solar Nebula)
b t = 7 Myr
c t = 10 Myr
(Nebula Dissipated)
Seed
Core
Solid Core
Gas
Solids: Dust Grains to Planetesimals
Gaseous Envelope

Disk Instability



Cameron (mid ‘70s)

Common Viewpoint

Heavy element core

$\Downarrow$

Core accretion model

Absence of Heavy element core

$\Downarrow$

Disk Instability Model

Correct Viewpoint

Heavy element core

$\Downarrow$ $\Downarrow$

Core accretion

Disk instability and core rainout

But do you get the right mass core?

Absence of Heavy element core

ß $\Downarrow$

Disk Instability

Core Accretion and core dredge up

But is this efficient?

Correct Viewpoint

Heavy element core

⇓ ⇓

Core accretion

Disk instability and core rainout

Most likely

But do you get the right mass core?

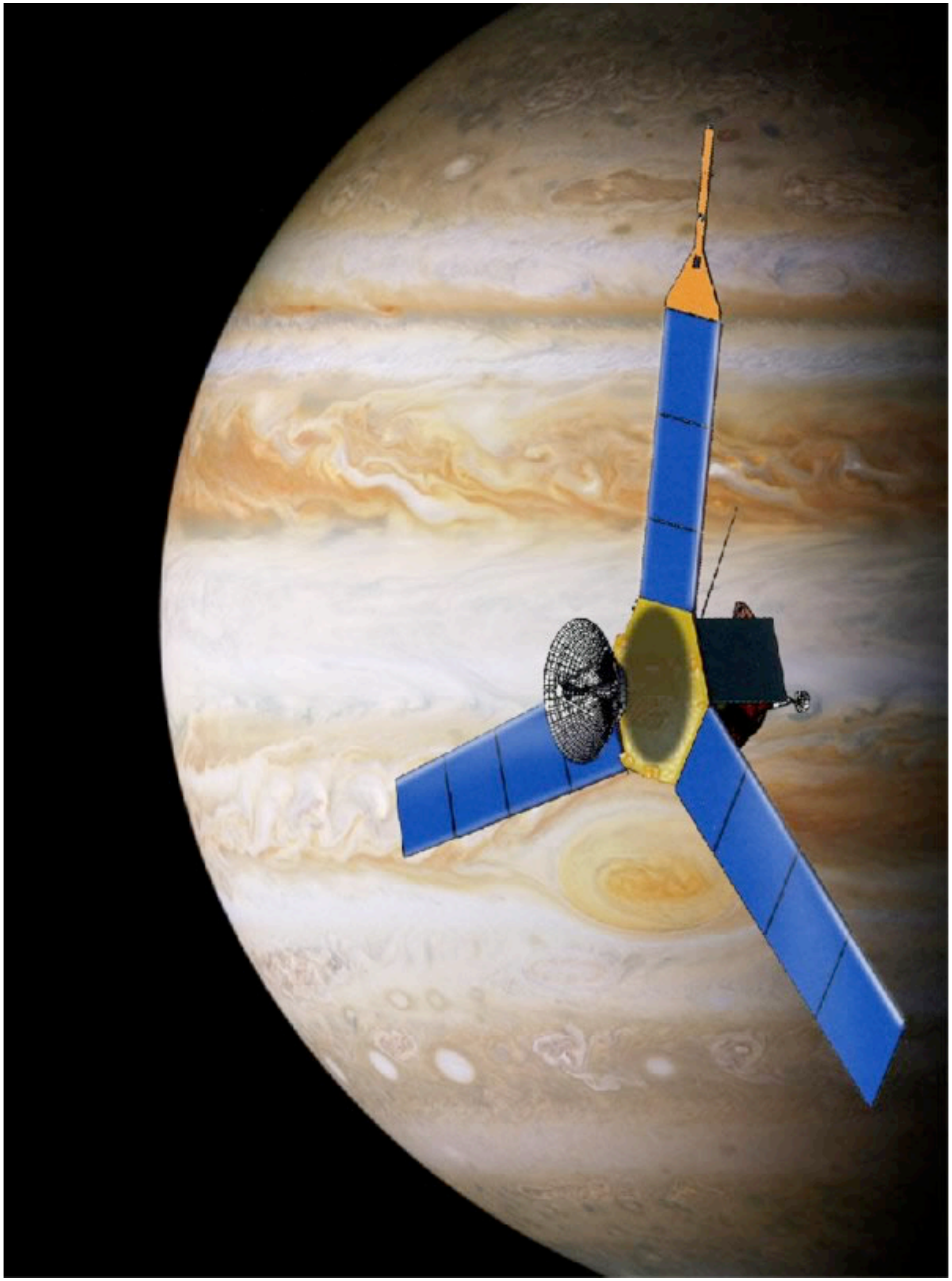
Absence of Heavy element core

ß ⇓

Disk Instability

Core Accretion and core dredge up

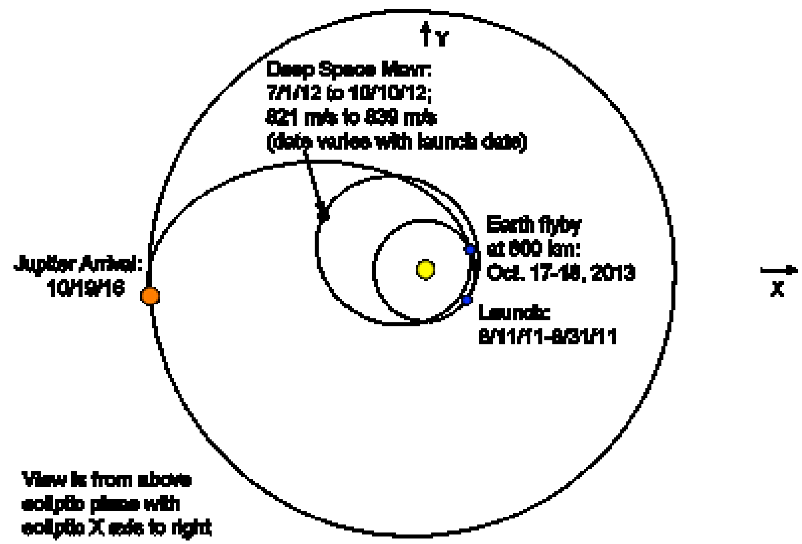
But is this efficient?



Juno

Billion dollar mission

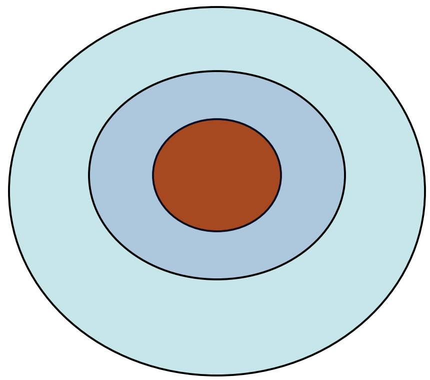
Planned for launch in 2011



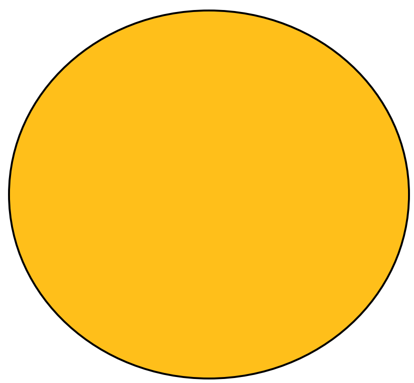
What does atmospheric Composition tell us?

- Presence of heavy noble gases at 3 x solar suggest incorporation of material that formed at very low T (~40K).

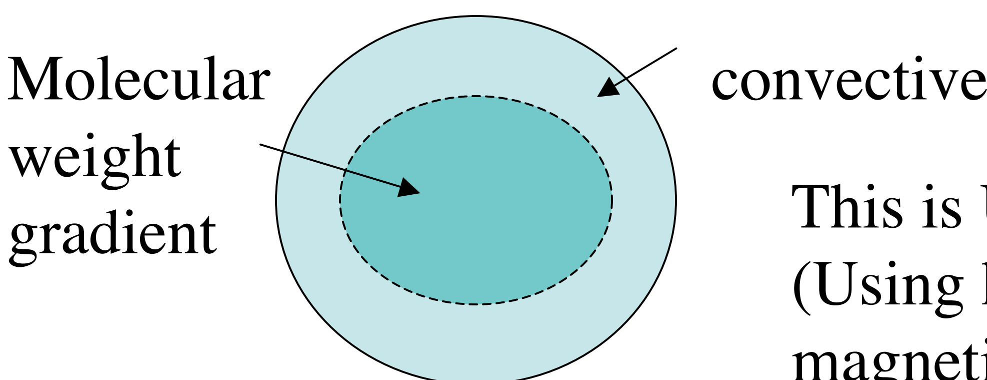
Uranus J_2 , etc tell us that…



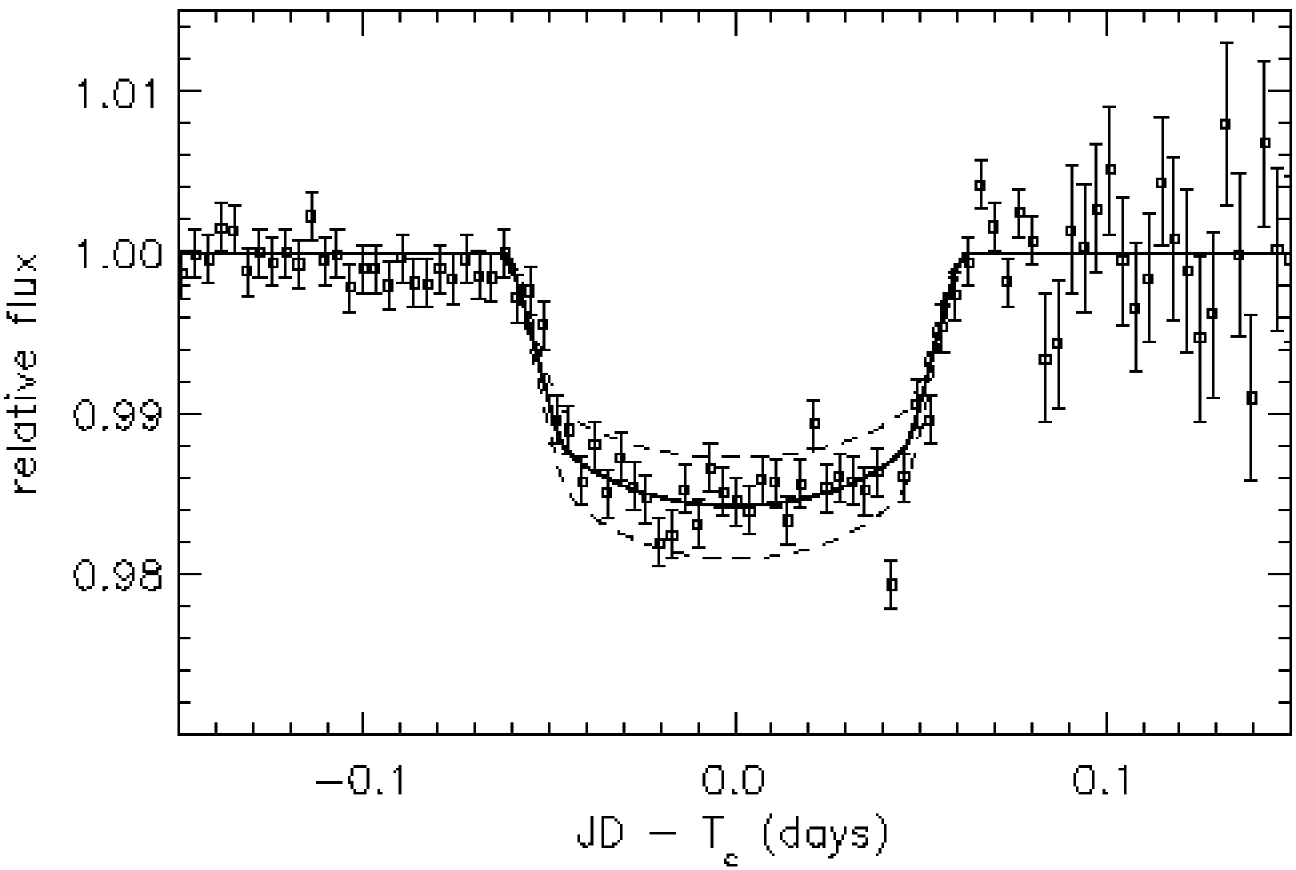
This is not Uranus
(Layercake)



This is not Uranus
(all mixed up)



This is Uranus?
(Using heat flow, magnetic field, etc)



HD209458 transit, 1999

Hot "Jupiters"

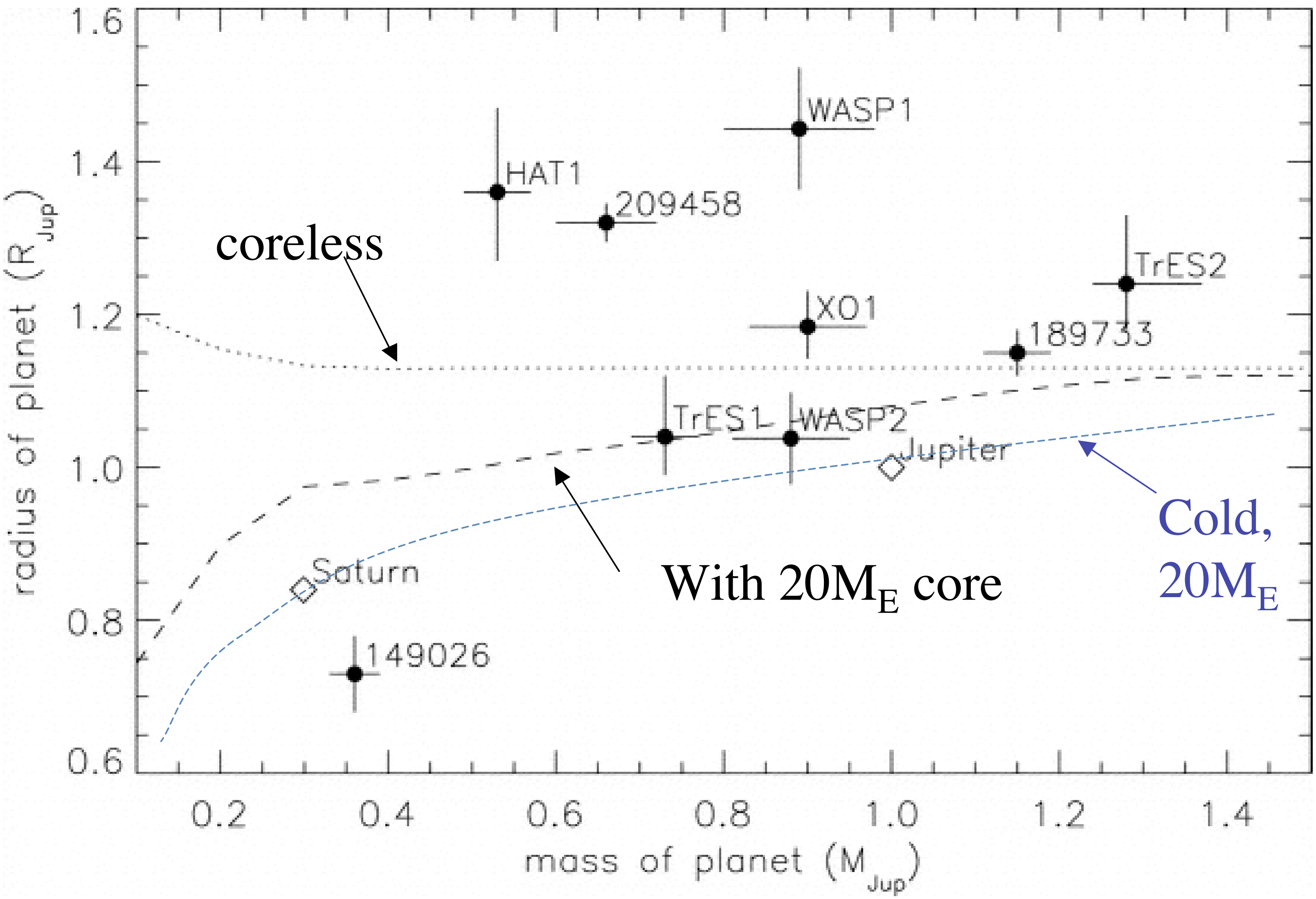
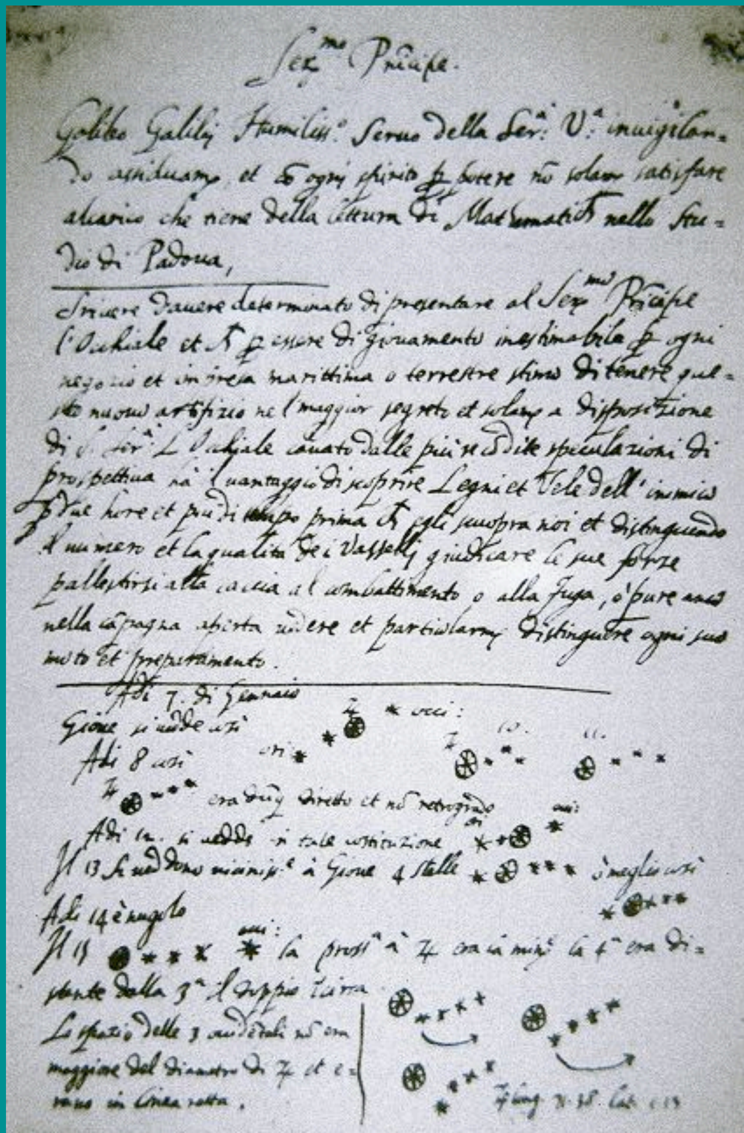


Figure from Charbonneau et al, 2007



The Galilean satellites were the first planetary system (other than our own) to be discovered.

We know a lot about it …..And it may be diagnostic

Satellites of extrasolar planets?

Solid particles in the solar nebula

?

Physical & chemical processes

Earth and Moon

(As we see them now)

?

Meteorites

?

Geochemistry & geophysics

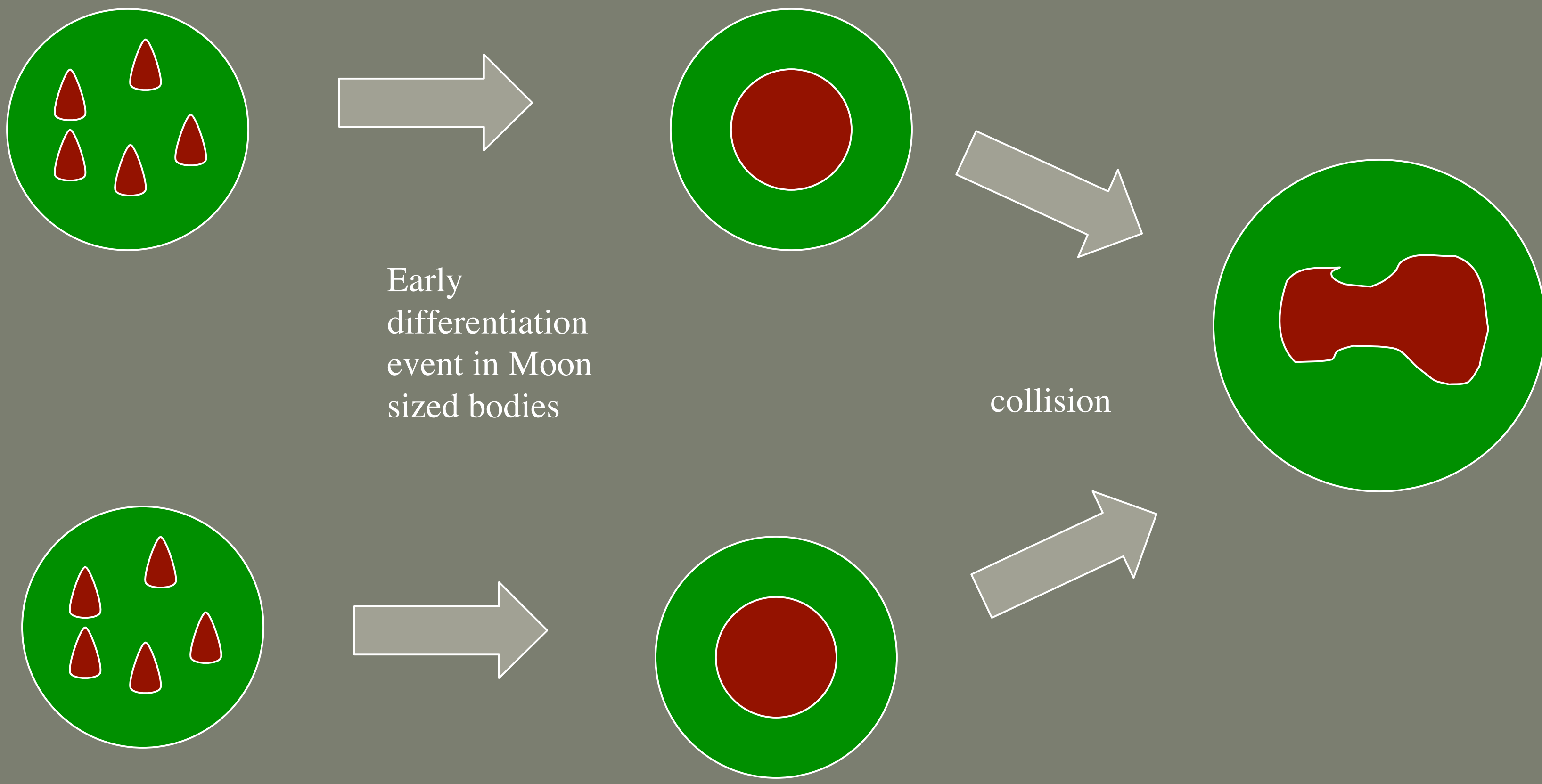
Central importance of melting

Likely importance of vaporization (of rocks)

GM/RL ~ 1

Processes of Core Formation

- **Cores form in Precursor Bodies (Moon to Mars in size…possibly because of ^{26}Al)** ***and these cores then merge during giant impacts***
- Core formation occurs through Rayleigh -Taylor instabilities at the base of an evolving magma ocean
- Core formation is the aftermath of giant impact emulsification (impact, R-T and K-H mixing)



CORE MERGING EVENT

(Hf-W timescale ≠ planet formation timescale)

Processes of Core Formation

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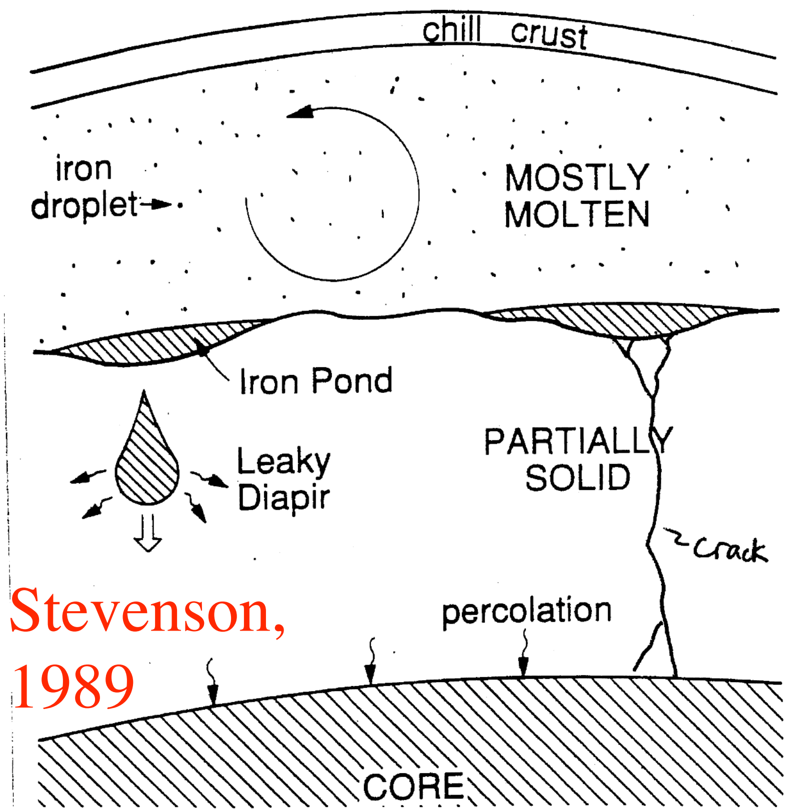
Popular Cartoons of Core Formation



Stevenson, 1989

Wood et al, 2006

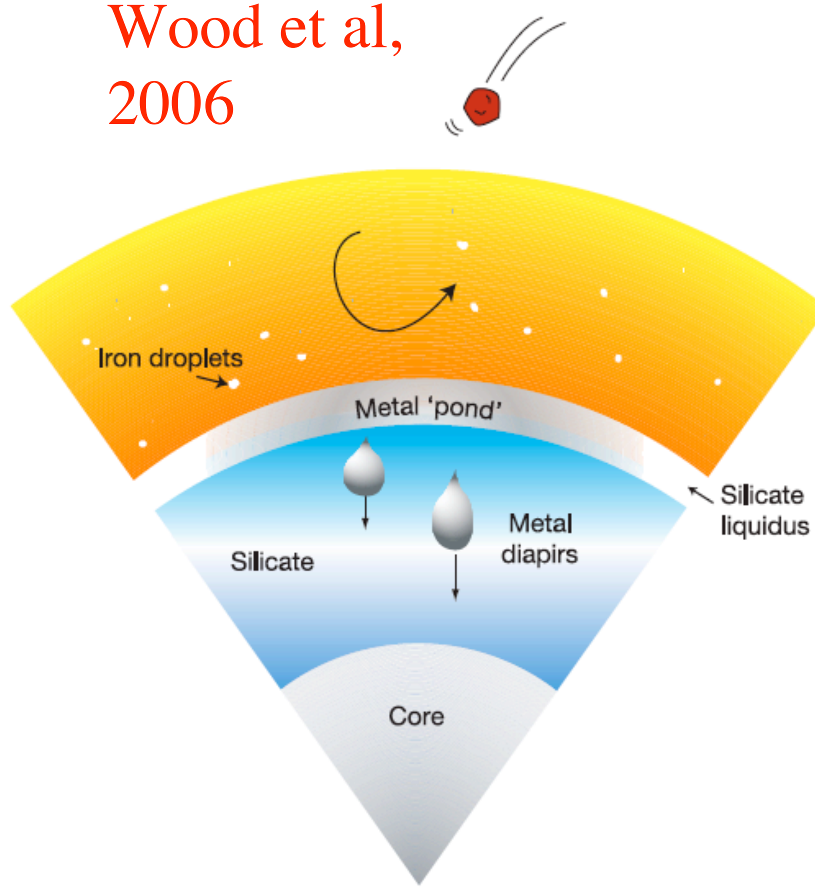


Figure 3 | The deep magma ocean model. Impacting planetesimals disaggregate and their metallic cores break up into small droplets in the liquid silicate owing to Rayleigh–Taylor instabilities. These droplets descend slowly, re-equilibrating with the silicate until they reach a region of high viscosity (solid), where they pond in a layer. The growing dense metal layer eventually becomes unstable and breaks into large blobs (diapirs), which descend rapidly to the core without further interaction with the silicate. Note that the liquidus temperature of the silicate mantle should correspond to pressure and temperature conditions at a depth above the lower solid layer and plausibly within the metal layer as indicated.

Processes of Core Formation

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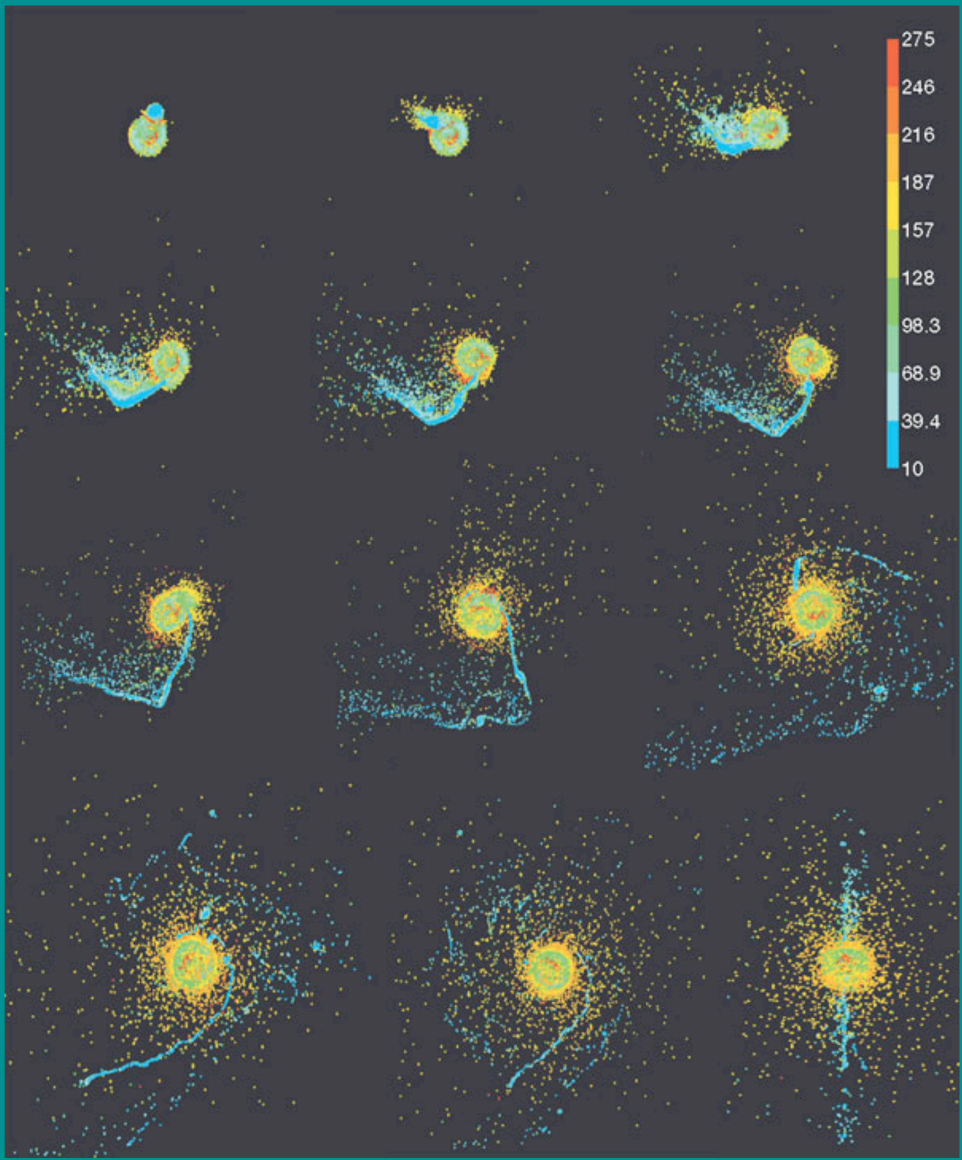
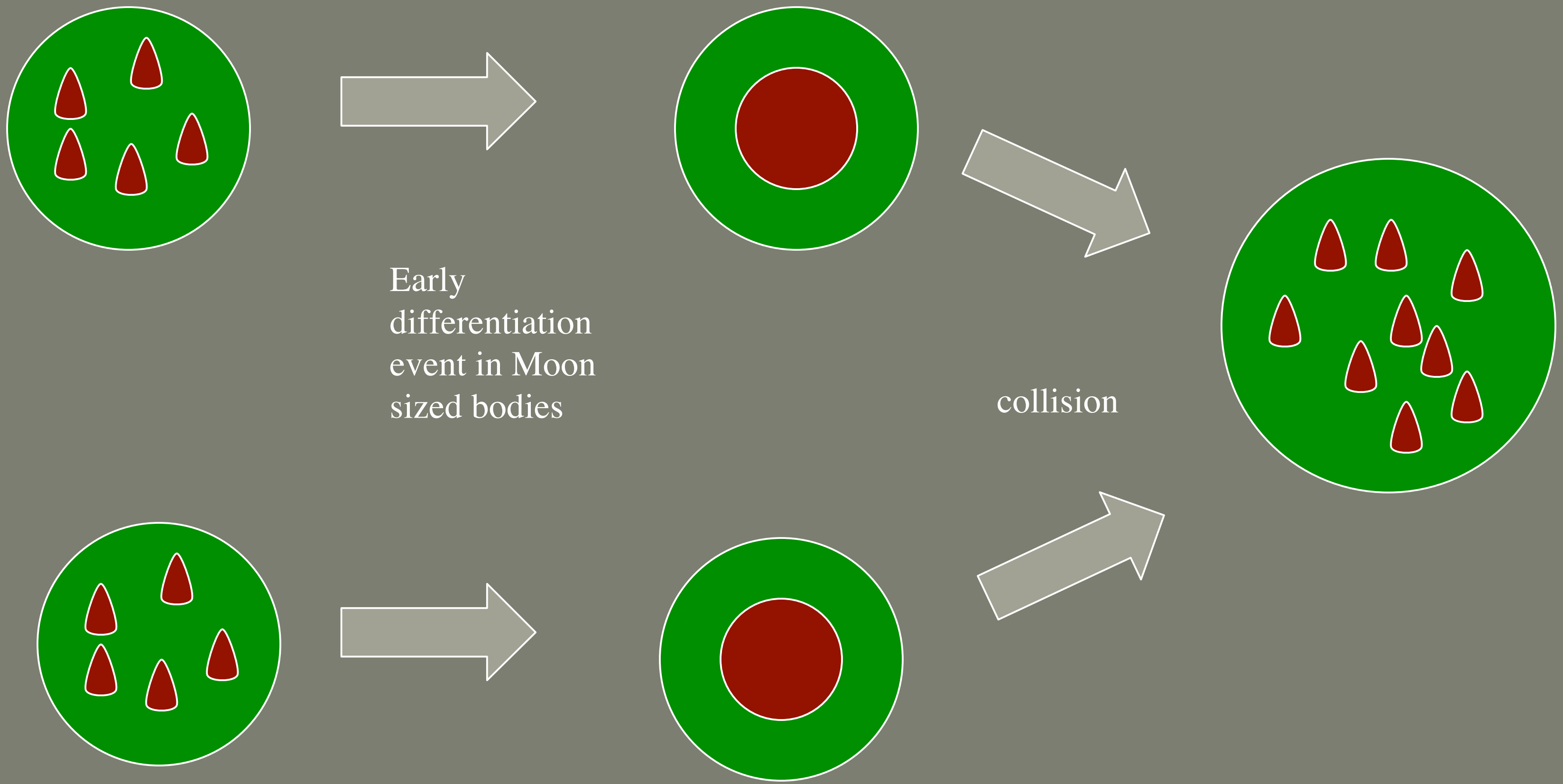
What Happens During a Giant Impact?



- Most of the material is melted; part is vaporized.
- Core of projectile is often intact and crashes into Earth, plunging to the core on a free fall time.
- Severe distortion (sheets, plumes; not spheres). But SPH does not indicate much direct mixing.

Canup & collaborators

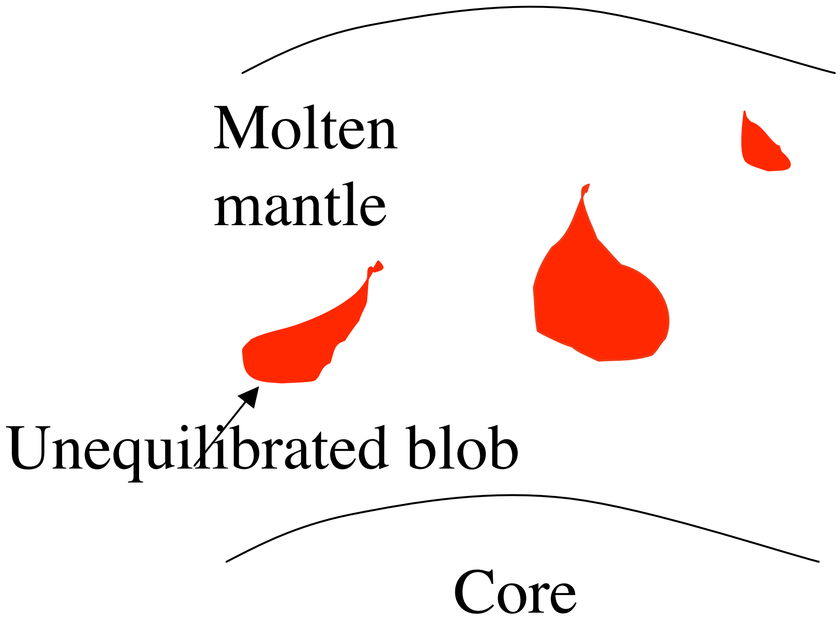


EMULSIFICATION DURING IMPACT

(Hf-W timescale ≈ planet formation timescale provided emulsification is sufficiently small scale and complete)

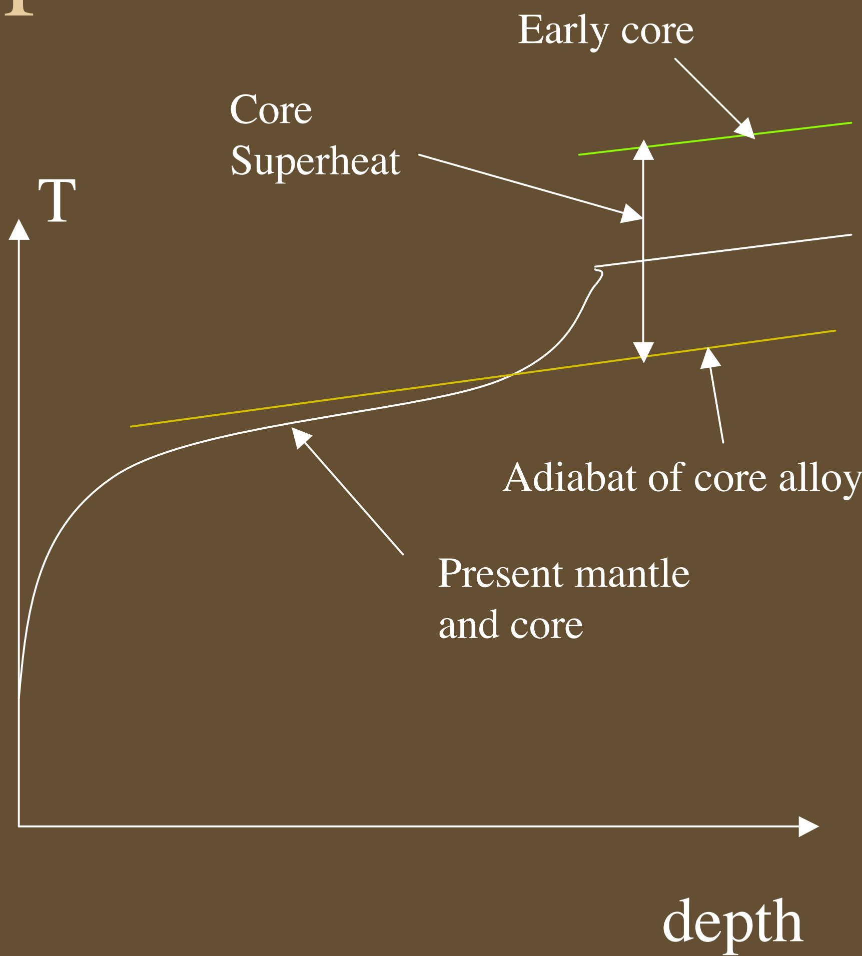
Core Formation with Giant Impacts

- Imperfect equilibration $\Rightarrow$ no simple connection between the timing of core formation and the timing of last equilibration
- No simple connection between composition and a particular T and P.



Core Superheat

- This is the excess entropy of the core relative to the entropy of the same liquid material at melting point & and 1 bar.
- Corresponds to about 1000K for present Earth, may have been as much as 2000K for early Earth.
- *It is diagnostic of core formation process*...it argues against percolation and small diapirs.

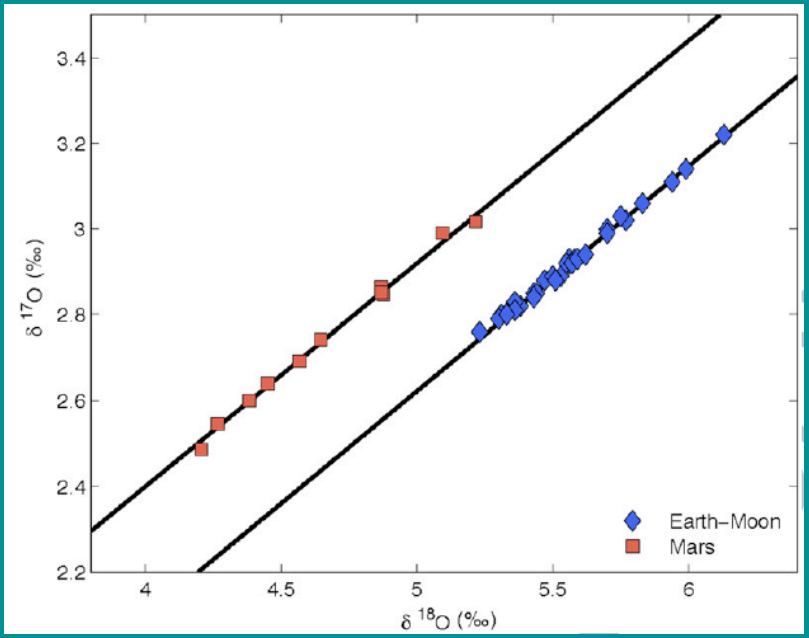


Formation of the Moon

- Impact “splashes” material into Earth orbit
- The Moon forms from a disk in perhaps ~100 years
- One Moon, nearly equatorial orbit, near Roche limit- tidally evolves outward

Oxygen Isotopes

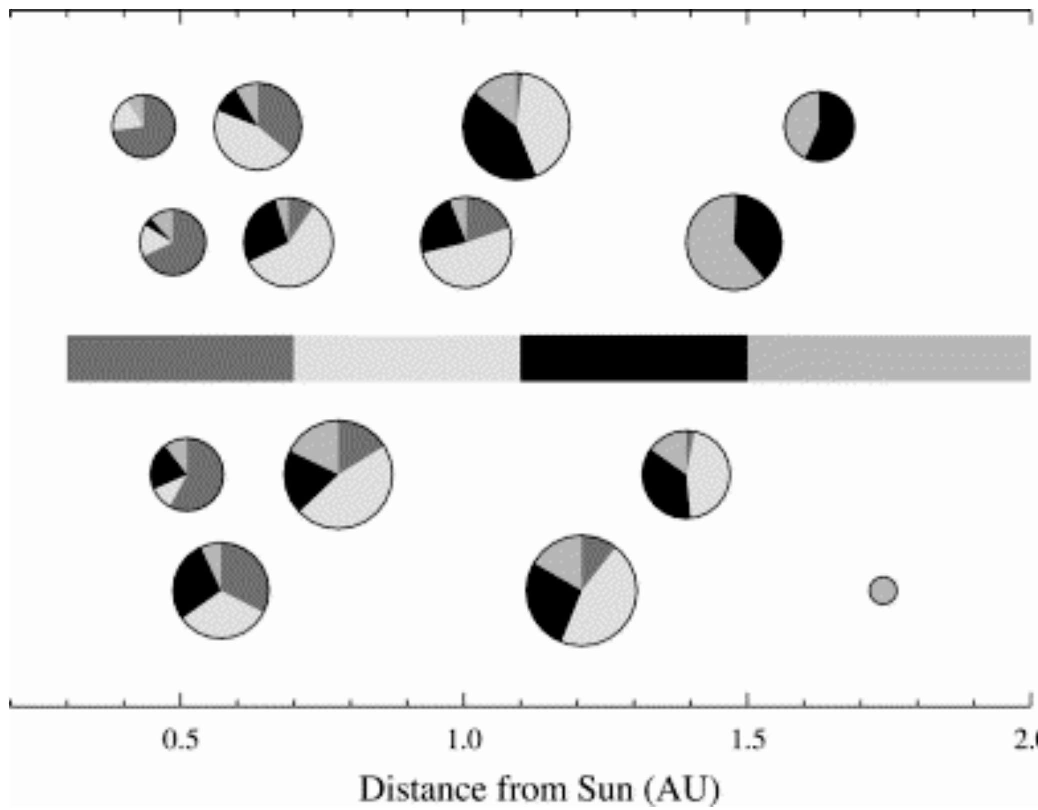
- Fundamental origin of the differences between Earth, Mars and meteorites is ***not understood***
- Still, the "identity" of Earth & Moon is often taken to imply same "source"



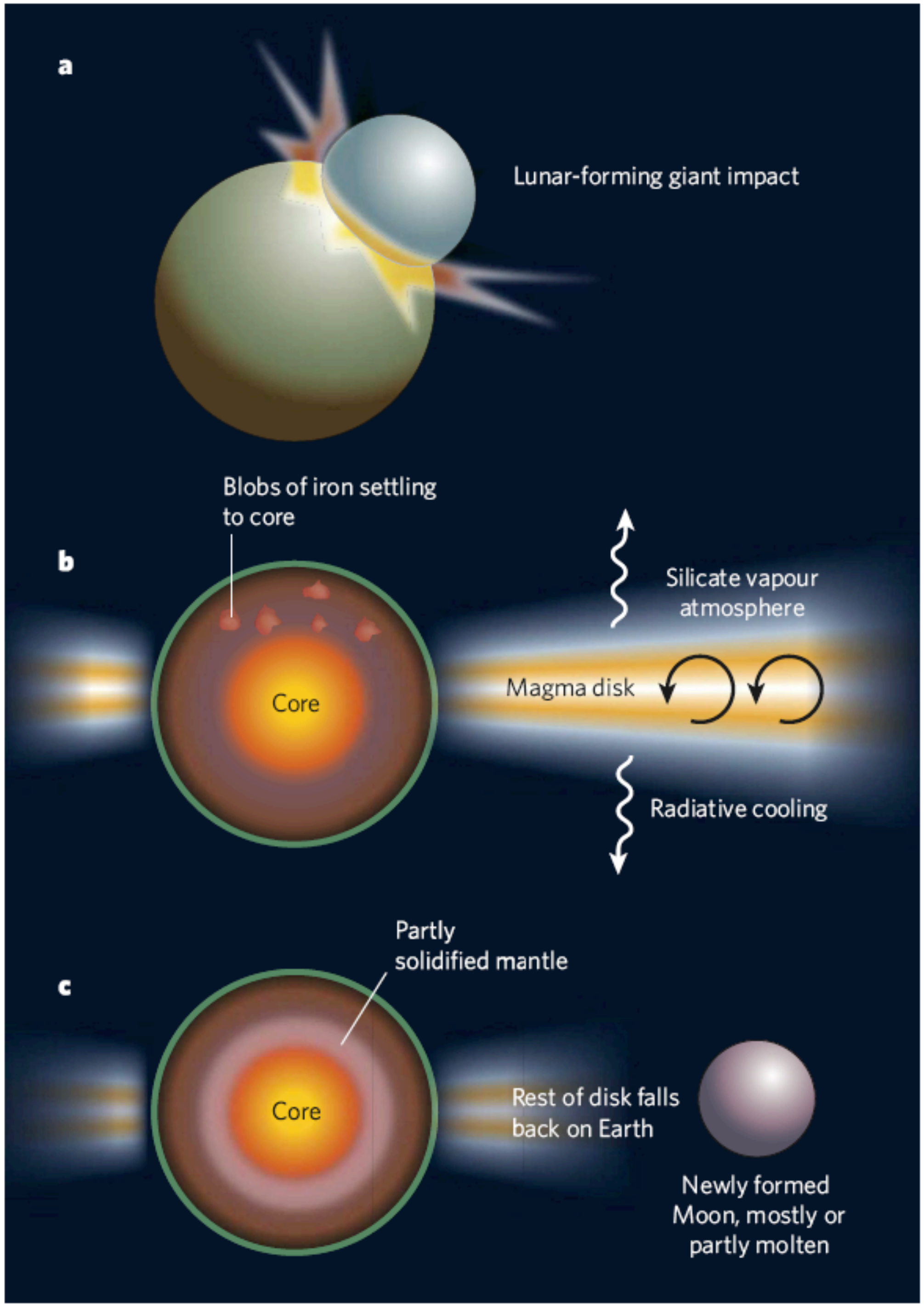
In current terrestrial accretion models, the material that goes into making Earth comes from many different regions

It is **very unlikely** that the Moon-forming projectile would have the same isotopic composition as protoEarth.

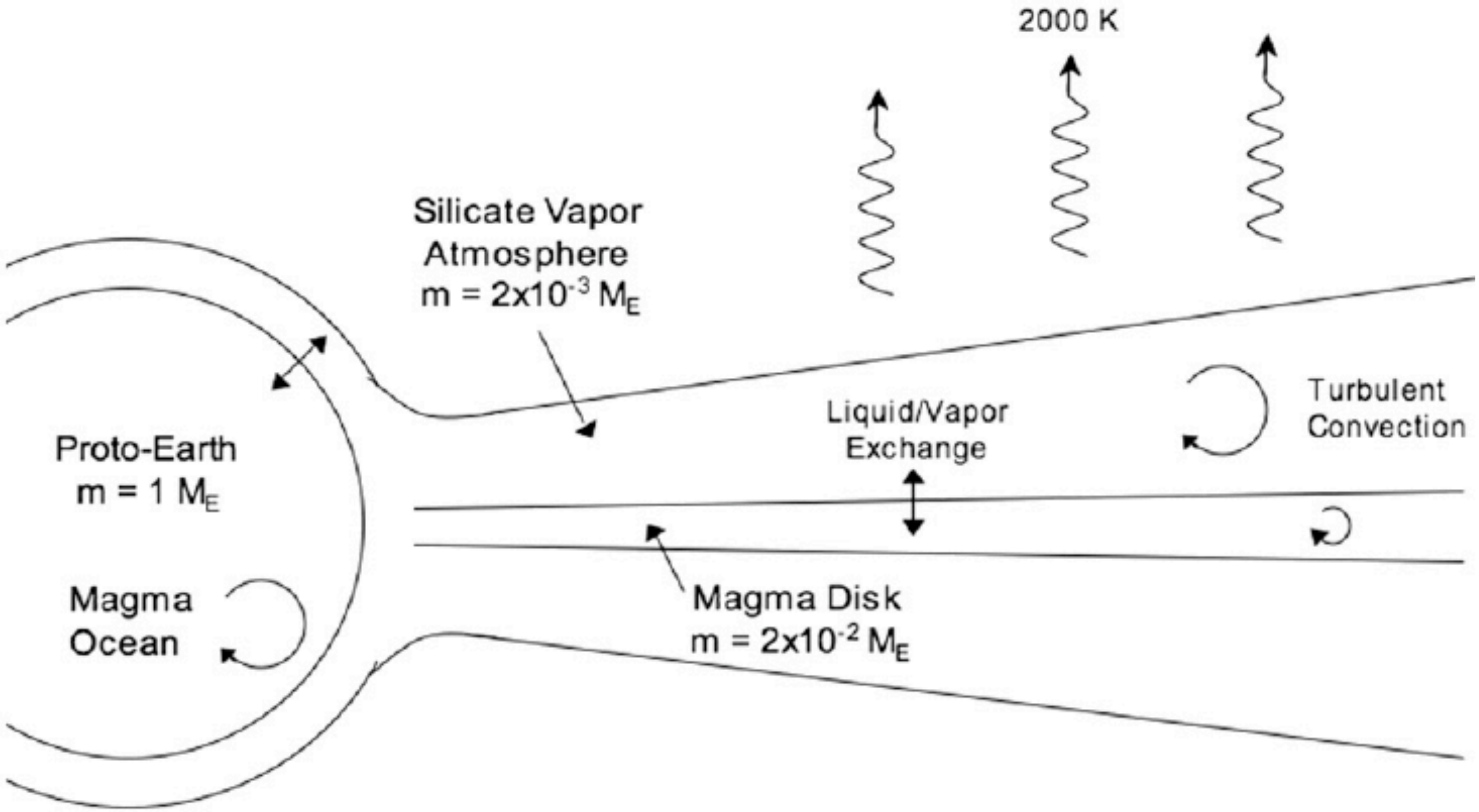
Zonation of composition in terrestrial zone is unlikely



Results from Chambers, 2003 (Similar results from Morbidelli)



Stevenson, *Nature* 2008



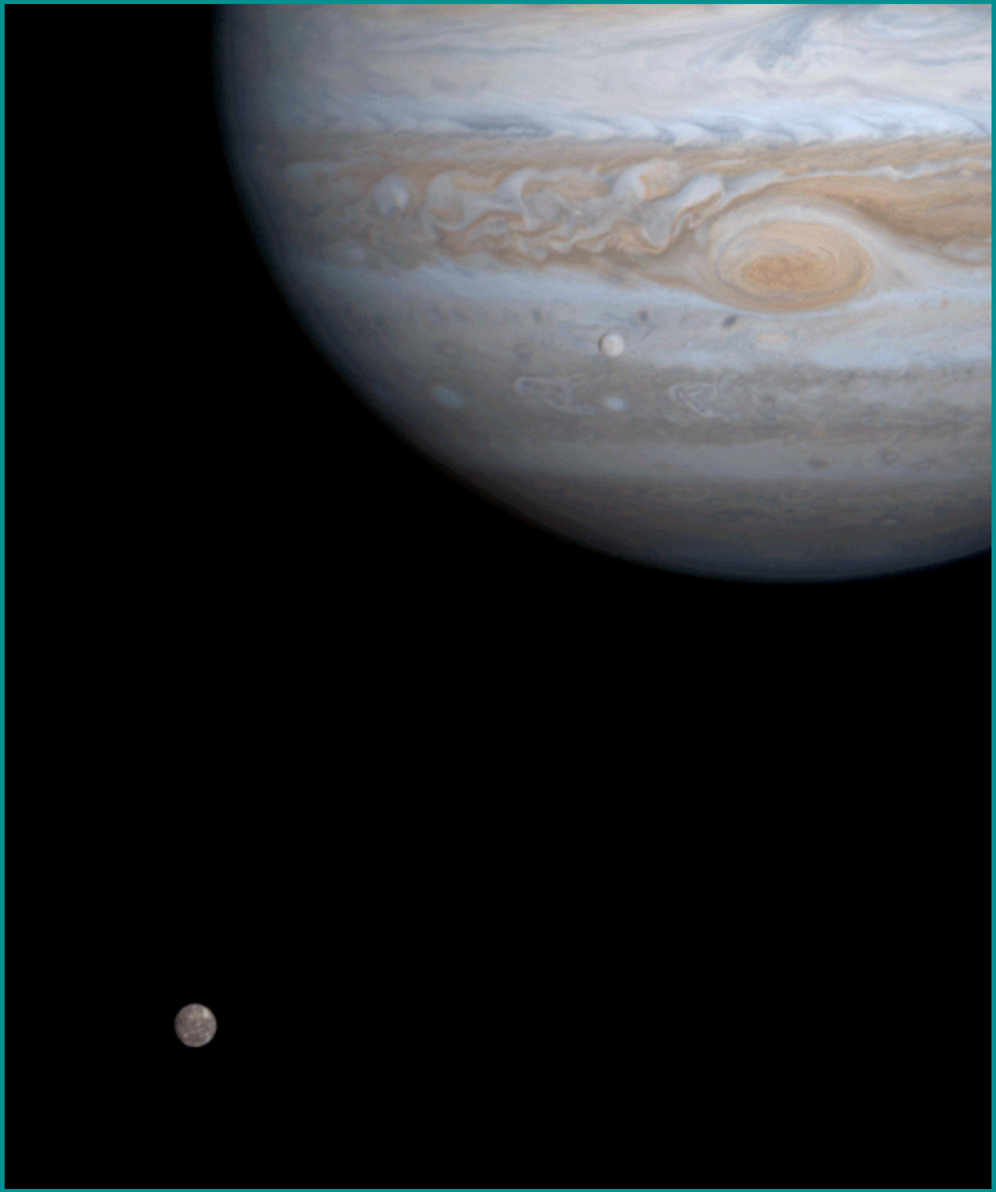
Pahlevan, K., Stevenson, D.J. Equilibration in the aftermath of the lunar-forming giant impact. Earth Planet. Sci. Lett. (2007), doi:10.1016/j.epsl.2007.07.055

Some Conclusions

(and some challenges)

- Cores of giant planets are testament to the embryo assembly followed by gas on top… but the process is messy (mixing) and there is evidence of small bodies contributing.
- Cores of terrestrial planets & nature of Earth's moon are testament to the high energy (giant impact) nature of assembly, but again there is a role for smaller bodies (dynamically and compositionally).

The End



Cosmic (~Solar) Abundances

Element	Number Fraction	Mass Fraction
H	0.92	0.71
He	0.08	0.27
O	7×10^{-4}	0.011
C	4×10^{-4}	0.005
Ne	1.2×10^{-4}	0.002
N	1×10^{-4}	0.0015
Mg	4×10^{-5}	0.001
Si	4×10^{-5}	0.0011
Fe	3×10^{-5}	0.0016